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Dynamics of eddy-resolving models of the Pacific Ocean and the Sea of Japan

Harley E. Hurlburt[1], Patrick J. Hogan[2], E. Joseph Metzger[1], William J. Schmitz, Jr.[3] and Alan J. Wallcraft[4]

Models with resolution up to 1/16° for the Pacific Ocean north of 20°S and up to 1/32° for the Sea of Japan are used to investigate the dynamics of the circulation in these domains. In both cases high horizontal resolution is critical in simulating the essential dynamics of the mean flow and variability on the mesoscale and some aspects of the larger scale flow. Among these are the mean path of the Kuroshio/Kuroshio Extension south and east of Japan, the separation of the flow connecting the Kuroshio Extension and the subarctic front from the east coast of Honshu, the eastward penetration of high variability in the Kuroshio Extension, the separation of the East Korea Warm Current from the east coast of Korea and the abyssal circulation in the Sea of Japan.

Figure 1 shows the mean and a snapshot of sea surface height (SSH) from a 1/16° version of the NRL Pacific Ocean model. The model simulates the main gyres and current systems, including most of those in the marginal seas. Meandering currents and eddies are ubiquitous. Figure 2 shows the mean SSH in the northwest Pacific and adjacent deep marginal seas from (a) a nearly linear solution (b) a nonlinear flat bottom simulation and (c) a simulation with realistic bottom topography. All three show the subpolar and subtropical gyres and a double frontal structure representing the subarctic front (42°-45°N) and the Kuroshio Extension (32°-36°N in the simulations).

The subarctic front is the boundary between the subtropical and subpolar gyres. It is associated with the annual mean and Apr-Nov mean zero wind stress curl (which are similar) while the Kuroshio Extension is interior to the subtropical gyre and it is associated with the winter time zero wind stress curl. This means part of the flow from the Kuroshio must pass north of the Kuroshio Extension and connect with the Oyashio and the subarctic front. Part of this connecting flow is through the Sea of Japan but in the linear and flat bottom simulations some of it flows northward in an unrealistic northward boundary current along the east coast of Japan. In addition the Kuroshio Extension is 2 to 3° too far south and the mean meanders south and east of Japan are not realistically represented. The only difference between the simulations in figures 2b and 2c is the addition of realistic bottom topography in figure 2c. This gives striking improvement in relation to the shortcomings of the linear and flat bottom simulations. These and other simulations (Hurlburt et al, 1994) show how the combined effects of baroclinic instability and specific topographic features bring about these improvements.

In essence the topography regulates the location and strength of the baroclinic instability. The baroclinic instability gives eddy driven deep mean flows that follow the f/h contours of the bottom topography. These abyssal currents then strongly influence the pathway for subtropical gyre flow north of the Kuroshio Extension and steer the mean meanders in the Kuroshio south and east of Japan. This is corroborated by current meter data from the Kuroshio Extension Regional Experiment (WOCE line PCM-7) (Z. Hallock, personal communication).

[1] Naval Research Laboratory
Stennis Space Center, MS 39529 USA

[2] Sverdrup Technology, Inc.
Stennis Space Center, MS 39529 USA

[3] Woods Hole Oceanographic Institution
Woods Hole, MA 02543 USA

[4] Planning Systems, Inc.
115 Christian Lane
Slidell, LA 70458 USA

Resolution of 1/8° in an ocean model is comparable to the 2.5° resolution used in atmospheric forecast models in the early 1980s based on the 1st internal mode Rossby radius of deformation. Model comparisons at 1/8° and 1/16° resolution and comparisons with current meter data and Geosat altimeter data show that 1/16° resolution is needed for adequate eastward penetration of the high EKE associated with the Kuroshio Extension (Fig. 3). Comparisons of figures 1 and 2c show the mean flow patterns depicted by the SSH are also improved.

The Pacific simulations shown in figures 1 and 2 show serious shortcoming in the Sea of Japan. Most notably, these are current separation from the west coast of Korea too far north and too little flow along the west coast of Japan. Isopycnal outcropping in the model is required to maintain a robust current along the west coast of Japan. This requires a shallower top layer than present in the Pacific Ocean simulations. Figures 4 and 5 show the results from Sea of Japan models with a shallower top layer and horizontal resolution ranging from 1/8° to 1/32°. These show the importance of high resolution (about 3.5 km in this case) and the bottom topography. Figure 5 shows that the importance of the bottom topography is missed at 1/8° resolution in the Sea of Japan. The separation latitude of the East Korea Warm Current is realistic only in the 1/32° simulation with realistic bottom topography. The basic dynamics are similar to those described earlier for the Kuroshio/Kuroshio Extension. Particularly striking is the reversal of the abyssal circulation as the resolution is increased from 1/8° to 1/32° (Fig. 4 d-f). In general baroclinic instability plays a critical role in coupling the shallow and abyssal layer circulations and in allowing the bottom topography to strongly influence the shallow circulation (Figs. 2, 4 and 5).

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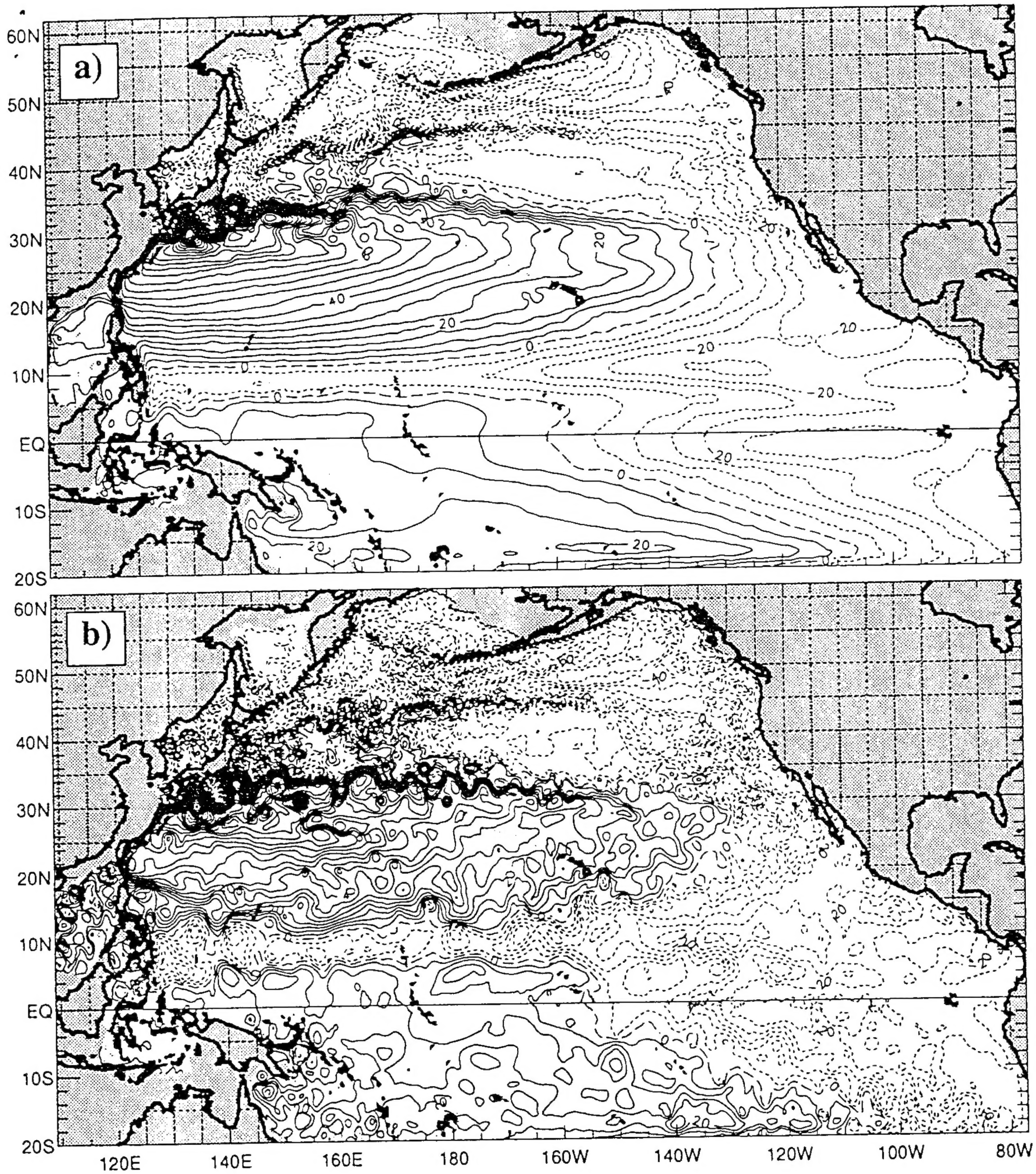


Figure 1. Whole domain (a) mean and (b) a snapshot of sea surface height (SSH) from a 1/16° 6-layer Pacific Ocean model with realistic bottom topography. The model was forced by the Hellerman and Rosenstein (1983) monthly wind stress climatology (HR winds). It was spun-up from rest to statistical equilbrium at 1/4° resolution, then continued at 1/8° and finally at 1/16° resolution. This wind forcing and this type of spin-up procedure were used in all simulations unless otherwise noted. Laplacian horizontal friction was used and the eddy viscosity (A) is 30 m^2/s. The dashed contours are negative and the contour interval is 5 cm. The exact resolution is 1/16° x 45/512° (lat,long) (between like variables) and all the simulations have lat, long resolution in this ratio. The model was developed at the Naval Research Laboratory (Hurlburt and Thompson, 1980; Wallcraft, 1991; Hurlburt et al., 1992).

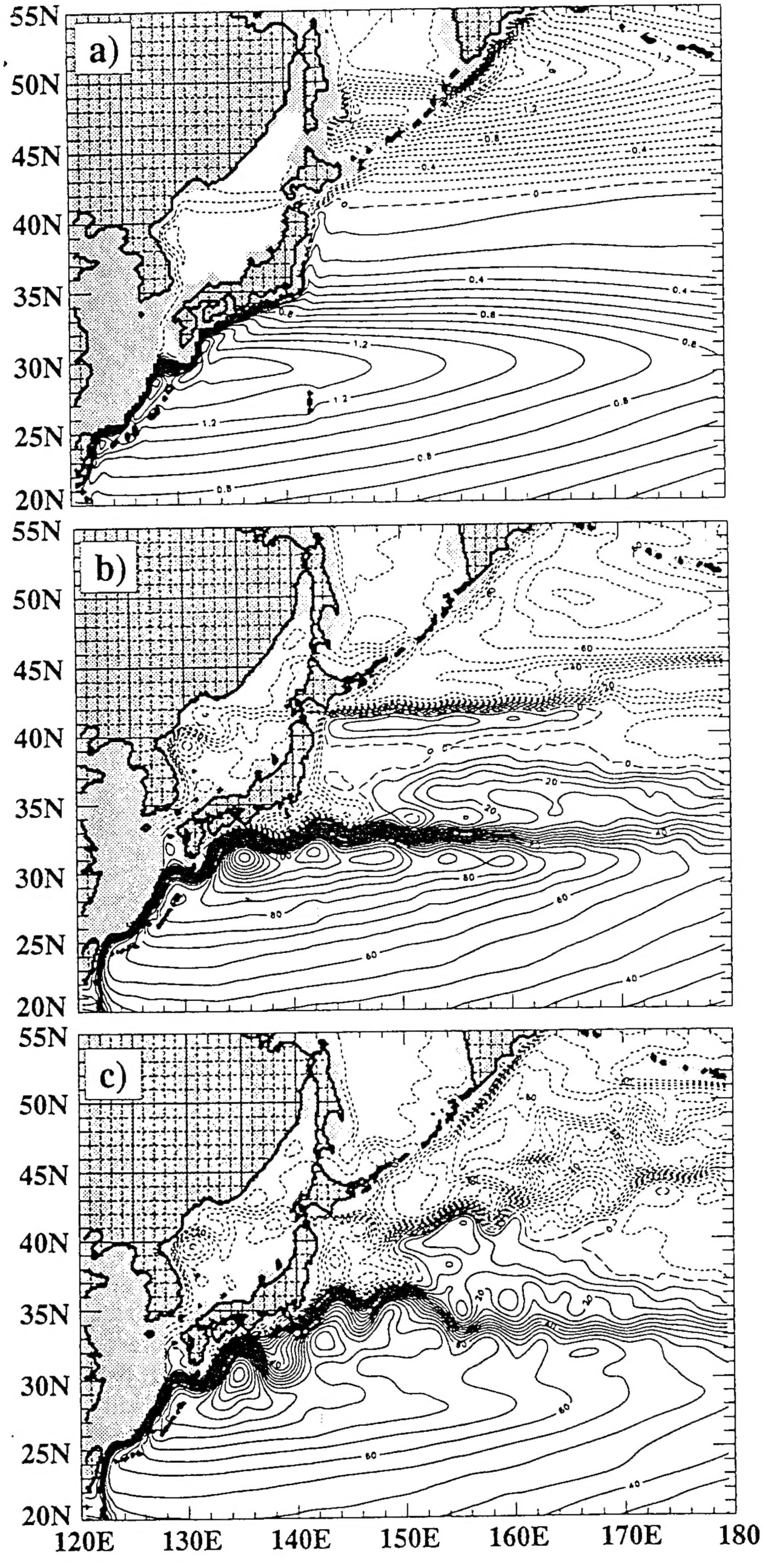
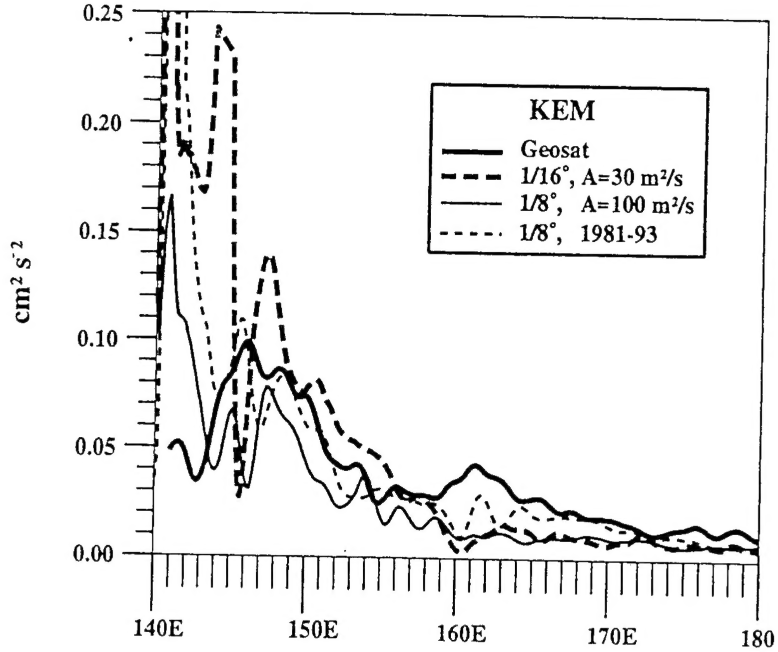


Figure 2. Mean SSH in the northwest portion of the model domain from three Pacific Ocean simulations north of 20°S. (a) A nearly linear simulation from a 1/4° 1.5 layer reduced gravity model (a two-layer model with the lowest layer infinitely deep and at rest). This is essentially the Munk (1950) solution redone with realistic coastline geometry and the HR winds and flow through the Sea of Japan constrained to have about one tenth the transport of the Kuroshio transport south of Japan. The HR wind amplitude was reduced by a factor of 100 to obtain near linearity in the ocean model response. (b) A nonlinear 1/8° 6-layer flat simulation and (c) a 1/8° 6-layer simulation with realistic bottom topography confined to the lowest layer. The contour intervals are (a) .1 cm and (b, c) 5 cm. The eddy viscosities are (a) 300 m^2/s and (b, c) 100 m^2/s.



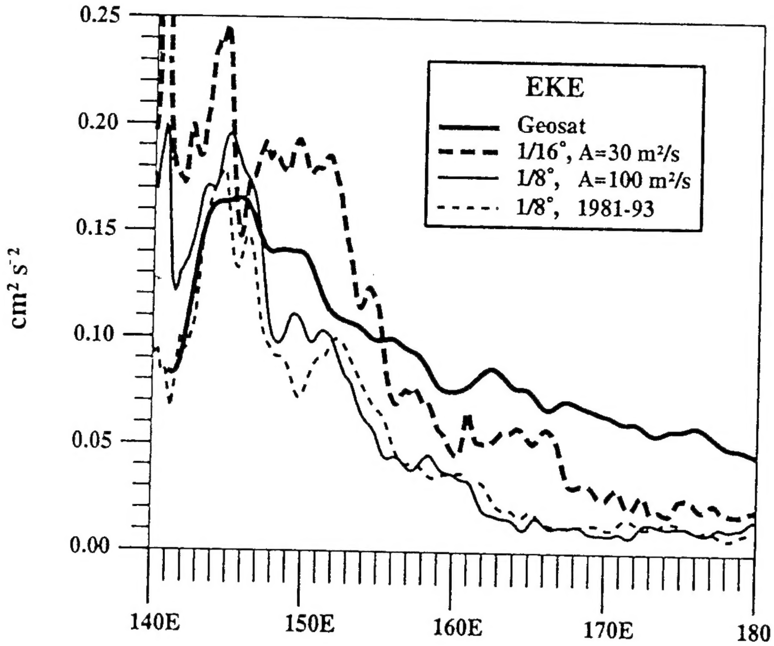


Figure 3. Model - Geosat comparisons of kinetic energy of the mean flow (KEM) and eddy kinetic energy (EKE) vs longitude averaged between 33° and 37°N in the Kuroshio Extension region. The Geosat values are from Qiu et al. (1991). The model values are from the 1/16° simulation of figure 1, the 1/8° simulation of figure 2c and the simulation of figure 2c extended 1981-93 using daily ECMWF 1000 mb winds with the 1981-91 mean replaced by the annual mean from Hellerman-Rosenstein.

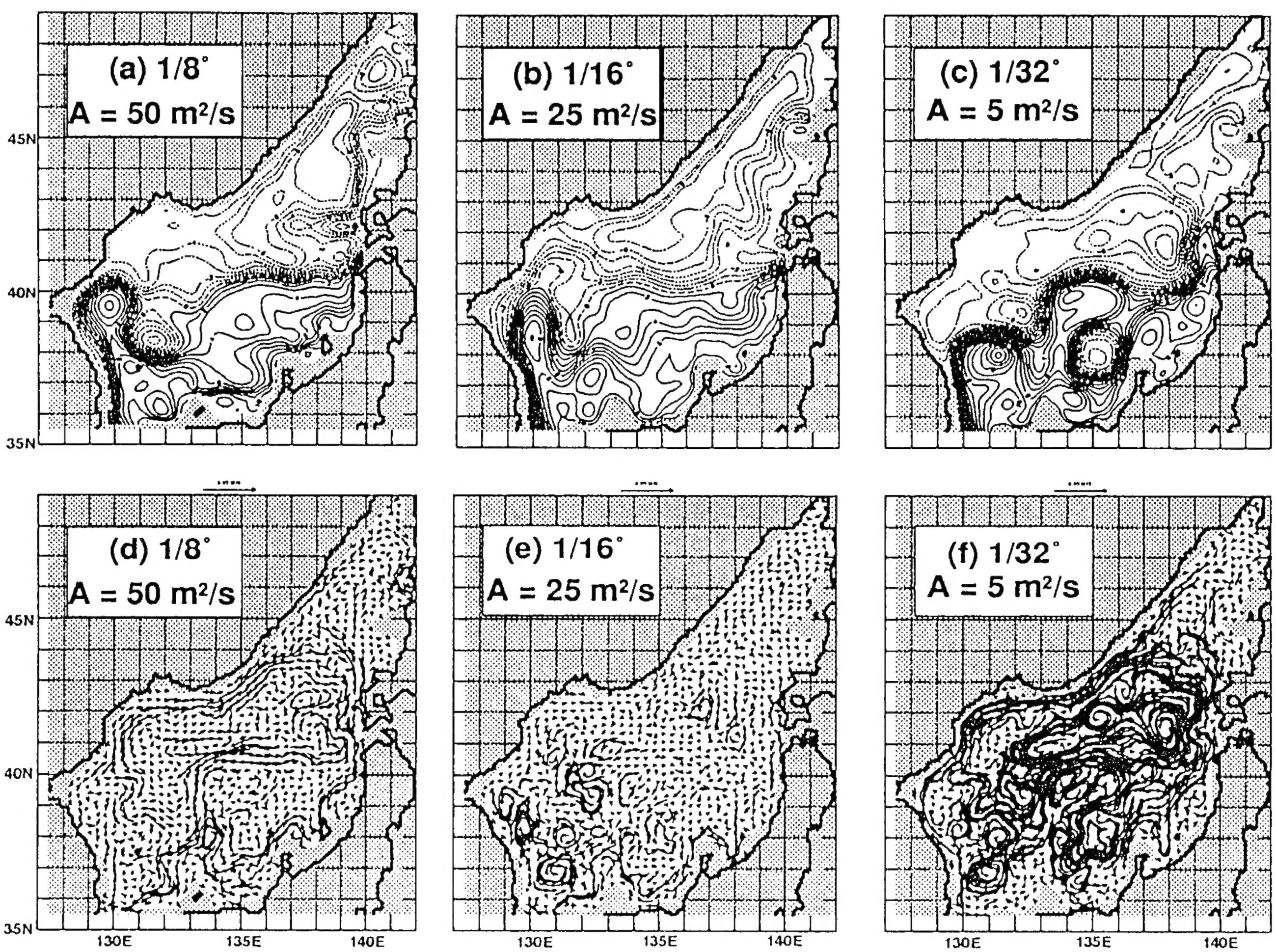


Figure 4. Mean SSH (a-c) and mean abyssal layer currents (d-f) from 4-layer Sea of Japan models with different resolution and realistic bottom topography. The contour interval is 1.0 cm. The model is forced by HR winds and flow through Tsushima, Tsugaru and Soya straits. The mean inflow transport through the Tsushima Strait is $2 \times 10^6 m^3/s$ (2 Sv) with outflow through the Tsugaru (2/3) and Soya (1/3) Straits. This transport has a sinusoidal seasonal cycle with a maximum of 3 Sv in summer and a minimum of 1 Sv in winter. Resolution of 1/32° is approximately equal to 3.5 km. The abyssal circulation is anticyclonic at 1/8° and cyclonic at 1/32°.

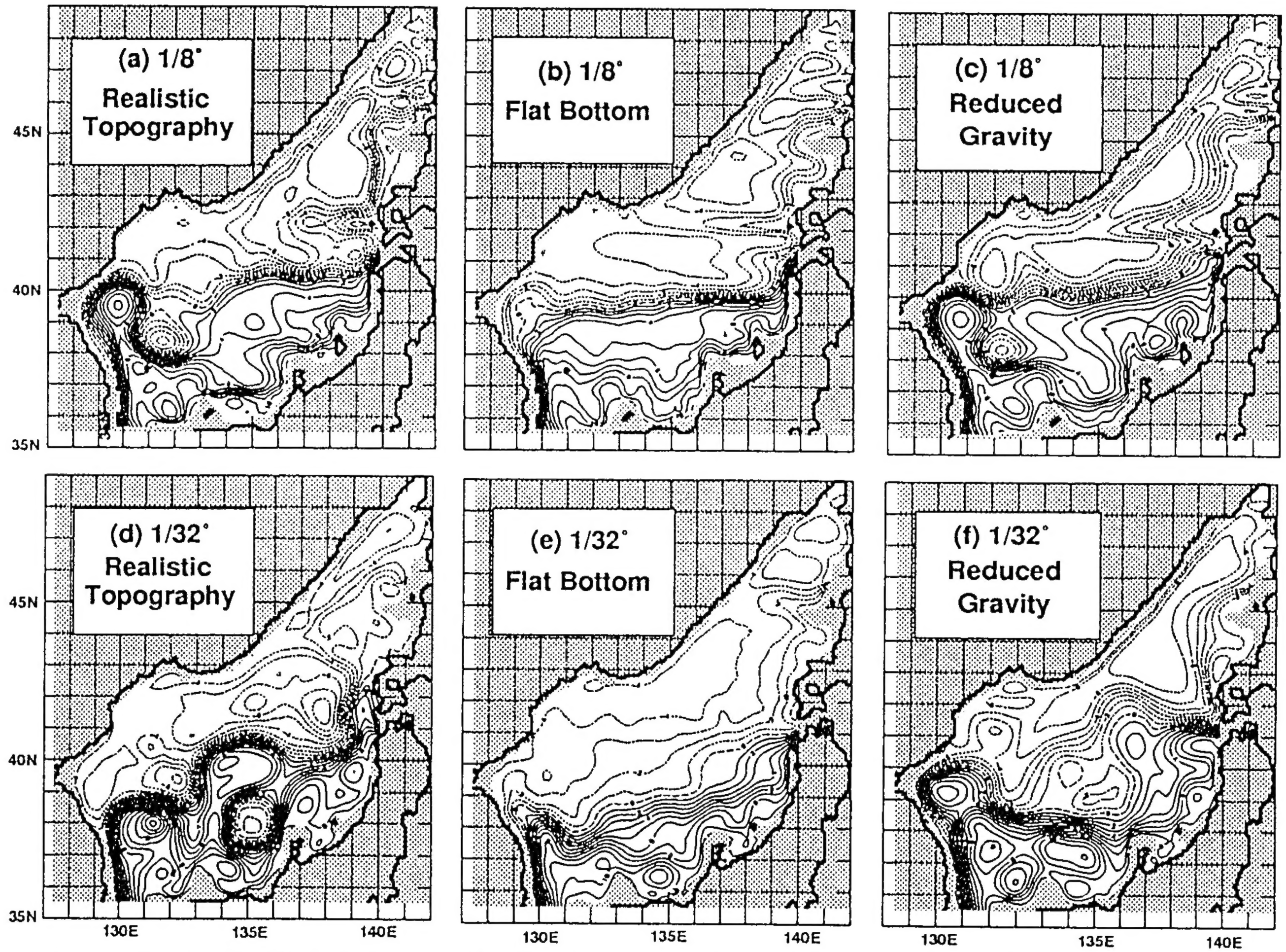


Figure 5. Mean SSH from simulations using (a,d) a 4-layer model with realistic bottom topography, (b,e) a 4-layer flat bottom model and (c,f) a 3.5 layer reduced gravity model. The forcing is the same as figure 4. The contour interval is 1.0 cm. The eddy viscosity (A) is 50 m^2/s for the 1/8° simulations and 5 m^2/s for the 1/32° simulations.

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Harley E. Hurlburt[1], Patrick J. Hogan[2], E. Joseph Metzger[1], William J. Schmitz, Jr.[3] and Alan J. Wallcraft[4]

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[1]Naval Research Laboratory
Stennis Space Center, MS 39529

[2]Sverdrup Technology, Inc.
Stennis Space Center, MS 39529

[3]Woods Hole Oceanographic Institution
Woods Hole, MA 02543

[4]Planning Systems, Inc.
115 Christian Lane Slidell, LA 70458

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